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WOOD AND OTHER RENEWABLE RESOURCES

A multi-criteria decision-making model for classifying wood products with respect to their impact on environment

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Abstract
Background, aim and scope Although life cycle assessment is frequently used in scientific studies of product comparison, many practitioners are looking for improvements in the normalisation, grouping and weighting of life cycle inventory results. Local conditions, which are well known to local experts, are very important to these steps. The goal of this work was to develop a computer-based decision support system for classifying wood products according to their influence on the environment in their whole life cycle. The model specifically addresses local conditions in the Republic of Slovenia and was developed by Slovenian experts.

Materials and methods We used the approach of multi-criteria decision making (MCDM). We developed a multi-attribute model that includes key parameters that influence the burdening of environment. The parameters are organised into a hierarchical structure with several levels in such a way that they form a hierarchy with unidirectional hierarchical relationships between levels. The aggregation of parameter values is carried out by utility functions which were defined according to the analytic hierarchy process method on the basis of 52 experts' findings, which were gathered with the Delphi method in three rounds.

Results The main result is a multi-criteria model for the assessment of wooden products. The model consists of 104 criteria, grouped into 28 subtrees, addressing various processes of production. Each criterion in the model has an associated weight, and each entry criterion has an entry function. The model has been used to assess different product concepts with the purpose of supporting decision making for the environmentally most suitable product concept and for analysing products with the intention of finding out more environmentally friendly products.

Discussion The weights in the model indicate that a preliminary production of auxiliary materials and energy consumption represents the biggest impact of wooden products on the environment. In preliminary production, the most problematic are preservatives, coating systems and glues. In energy production, the most influential are gasoline and petroleum. Emissions are most affected through water and air, whereas solid wastes and energy emissions are less important. With wastewaters, the most critical is the presence of organic criteria. With waste air, more important is waste air appearing directly in the production and less the smoke gases from devices for acquiring heat and electricity.

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Conclusions The presented multi-attribute model is aimed at classifying and comparing products according to their environmental burden in the entire wood product life cycle. The comparison can be carried out not only at the level of entire products but is also decomposed into hierarchically structured criteria. The decomposition reveals distinctive advantages and disadvantages of a product compared to others. The MCDM approach enables a relatively easy adaptation of the model where the changes have only a local effect. Entry data can be provided either directly in a numerical form or indirectly through pairwise comparison of alternatives. The model is restricted in the sense that it specifically addresses local conditions and legislation of the Republic of Slovenia.

Recommendations and perspectives The parts of the model that address emissions depend on Slovenian legislation and would require an adaptation to other countries. Other parts are fairly general. In order to compare wood products with other alternative or substitutive products, the set of criteria had to be expanded. We also suggest expanding the model with the aspects of working conditions and socioeconomic consequences of production.

Keywords Analytic hierarchy process · Classification of products · Delphi method · Entry functions · Life cycle assessment (LCA) · Modelling · Multi-criteria decision making · Wood

1 Background, aim and scope

Environment preservation and protection belong to the greatest challenges the world has set for the next decade. The consequence is an increasing number of environmental protection organisations, environmental standards, legislative regulations and limitations forcing companies into production that impacts the environment as little as possible. Furthermore, the customers are becoming more ecologically aware and are deciding on purchasing products whose raw materials, production, usage and removal do represent less impact on the environment. Oblak (1999) said that if, in the past, environment protection with a specific product was considered of no consequence and unnecessary expense, it is an important marketable argument today and a fundamental reason for the products to be sold at all in the future.

Wood manufacturing companies are also facing these problems. Even though these companies manufacture natural material—wood—they use glues, coating systems, preservatives, artificial substances and other materials that can harm the environment. The materials cause different emissions during their preliminary production, in the phase of production of wooden product or in the phase of waste processing or recycling. Therefore, the manufacturers of these products are facing a dilemma: which materials to use, which production processes to choose and which products to produce in order to impact the environment as little as possible.

From the viewpoint of the wood industry, the environment is impacted by a number of factors: consumption of raw materials, glues, coating systems, preservatives, lubricants, energy—preliminary impacts on the environment; releasing of solid wastes (wood wastes, wastes of wood-based materials, artificial substances wastes, wastes from lacquering, etc.); burdening of air with smoke gases from fire places and with waste air appearing in production where wood dust, dissolvent and diluter vapours in gluing and lacquering are arising; appearance of wastewaters with organic and inorganic parameters, etc. These parameters have various effects on the environmental burden. There are several categories of impact, such as global warming, stratospheric ozone depletion, photochemical smog formation, eutrophication, human carcinogenicity, atmospheric acidification, aquatic toxicity, terrestrial toxicity, habitat destruction, depletion of non-renewable resources, waste heat, malodorous air and water, noise, etc. (Guinee et al. 2002; Rosselot and Allen 1999). The establishment and estimation of the influences on the environment, respectively, a comparison of all these influences among themselves due to every enumeration, therefore, presents an enormous problem that requires attention. With the methods known to date, it is possible to estimate environmental burden for every category of impact separately (Guinee et al. 2002). However, it is difficult to give an overall estimate from the results of each category because they are incompatible. If all the scores of impact categories for one product are higher than those for another, it is easy to assess which product is the most environmentally friendly. But this almost never happens in practice. If one product has a higher score for one category whilst the other has a higher score for some other categories, it becomes difficult to compare them and justify any assessment. The ISO standard 14040 recommends three steps in explaining the conclusions: normalisation, grouping and weighting. But there is no best available method and these steps are just optional steps of impact assessment. Usually, the researchers stop before these steps or use experts' opinions to make conclusions. Local conditions are also very important in the ranking of alternatives; for example, compounds that moderately contribute to acid rain may not be (any) environmental concern in areas where the soil is well buffered and acid rain is not a problem. These local conditions are well known by local experts, so it is much recommended to include their opinion in assessing the alternatives.

Expert opinion in the evaluation of alternatives is usually taken into account through different models based on methods of operation research, especially methods of multi-criteria decision making (MCDM). In ecological modelling problems, these are often used to represent and combine indicators, evaluate alternatives and provide decision support in general. In some recent applications, MCDM methods were used for decision support in recycling (Ardente et al. 2003), forest management (Leskinen et al. 2003; Zadnik 2006), process model development (Komuro et al. 2006), ecolabel and sustainable development (Lavallee and Plouffe 2004). Lenzen (2006) used MCDM and analytic hierarchy process for minimising uncertainty in impact and externality assessment. For normalisation of the results in the phase of life cycle impact assessment, Seppälä (2007) used a fuzzy MCDM approach. For the assessment of material and process alternatives, Cooper et al. (2008) suggest the use of decision trees and matrix computational structures.

The aim of the presented study was to develop a computer-based decision support system for classifying wood products regarding their influence on the environment in their whole life cycle. This study builds on results of a previous study where only emissions in the manufacturing process were modelled (Lipušček et al. 2003). The aim of the presented study was to develop a MCDM model based on local conditions in the Republic of Slovenia, which would enable not only calculating the final estimations of the differences in environment burdening among the studied products but also establishing distinct environmental advantages and disadvantages of a product compared to other products included in the research. The decision support system should serve Slovene wood manufacturing companies for critical judgement of products, ranking of product concepts and for support in decision making for environmentally most favourable products. However, by proper adaptation of some internal components (weights in particular), the model would become useful for other local conditions as well.

2 Materials and methods

The aim of the MCDM model is to classify wood products from the viewpoint of burdening the environment. The assessment takes into account the entire product's life cycle. Thus, a central entity assessed by the model is a wooden product. This product is described with values that represent its properties in terms of impacts on environment. The model aggregates these entry values into an overall assessment of the product's environmental impact. According to the principles of MCDM, the model has a hierarchical structure: The terminal nodes of the hierarchy represent entry parameters that are through several levels gradually aggregated into the final assessment.

We developed the model in the following steps:

1. Identification of key parameters that influence the burdening of environment in life cycles of wood products;
2. Creation of the hierarchical structure of the model;
3. Description of utility functions of the model;
4. Generation of entry functions.

2.1 Identification of key parameters that influence the burdening of environment in life cycles of wood products

Wood production uses different types of raw materials, substances and energy, which all have their own history of burdening the environment at their preliminary production. Also, there appear different emissions into water, air and soil during production, use and disposal of products. The production of a specific product consumes different quantities and different types of wood, glues, coating systems, preservatives, lubricants, energy from different sources, etc. Apart from solid wastes (wood wastes, wastes of wood-based materials, artificial substances wastes, wastes from lacquering and gluing), there are also emissions of smoke gases from fire places and wood dust, dissolvent and diluter vapours from lacquering, emissions of organic and inorganic substances in water, changes of temperature and the pH of wastewaters, emissions of noise in the surroundings, waste heat, etc. These factors were gathered from a life cycle inventory of different wood products. The procedure of gathering the criteria of burdening the environment during life cycles of wood products is described in detail in Lipušček (2005).

2.2 Creation of the hierarchical structure of the model

Determined parameters were structured and arranged hierarchically into a MCDM decision model. In principle, MCDM takes into account that there are several criteria (parameters) influencing the choice of an alternative, which are not all equally important and often contradictory. The decision problem (marked as estimation of environmental burden) is first of all decomposed into smaller sub-problems, represented by variables (often called criteria, parameters, attributes) x_i, i=1, 2, 3,…n, where n is the number of sub-problems. These can be further decomposed into smaller and smaller sub-problems. In this way, a decision-making model is acquired whose size and shape depend on the extensiveness and difficulty of the decision problem (Bohanec and Zupan 2002). The evaluation of alternatives v_k, k=1, 2, 3,…m, where m is the number of alternatives studied, is first carried out separately according

to all criteria x_i appearing at the lowest levels of the model (the so-called entry parameters which represent inputs of the model). The overall values of alternatives are then obtained by aggregation, which typically involves criteria weights (see Section 2.5 for more details).

In our model, the decision problem of assessment of environment burden caused in life cycle of wood products is first decomposed into two sub-problems: (1) burdening the environment during preliminary production of substance, materials and energy used in any phase of life cycle of product and (2) emissions appeared in the phases of production, use and disposal of products. Sub-problem (1) is further decomposed into four sub-problems: (1a) burdening the environment during the production of raw materials; (1b) lubricants; (1c) energy acquisition; and (1d) preparation of water for communal or industry use. Criteria (1a) are then divided into five sub-problems: burdening the environment during harvesting and production of sawn wood and cellulose; production of glues; coating systems; wood preservatives; and other materials used in wooden products. All the remaining sub-criteria were decomposed in a similar way, giving the structure presented in Fig. 3.

Sub-problem (2) is decomposed into: (2a) burdening the environment with solid wastes; (2b) emissions to waters; (2c) waste air; and (2d) energy emissions. Emissions to waters (2b) consist of three sub-criteria: burdening of waters with inorganic parameters; with organic parameters; and with general parameters. These three consist of 21, 11 and four sub-criteria, respectively, which were all taken from the Official Gazette of the Republic of Slovenia (OGRS No. 35/1996). Emissions to air (2c) are decomposed into emissions from production (OGRS No. 46/2002) and emissions from devices for energy acquisition. Emissions from production take into account emissions of wood dust (OGRS No. 73/1994) and emissions of inorganic, organic and carcinogenic substances, which include more danger groups. Descriptions of danger groups and the corresponding list of criteria are presented in OGRS No. 73/1994.

2.3 Description of utility functions of the model

Once the structure of the MCDM model has been defined, we constructed utility functions whose role in the model is to assess and aggregate the values of alternatives (wooden products). We used the analytic hierarchy process (AHP) method (Saaty 1994). AHP arises from a natural human ability for using information and experience for evaluating the pairwise comparisons which help us to calculate relative importance (weights) of individual criteria. AHP proceeds by a gradual comparison of pairs of criteria that occur at the same level of the model. A scale from 1 to 9 is used for comparison, where 1 means that two criteria are of equal importance and 9 means a very strong importance of one criterion over another. Mathematically, we have a set of criteria $\{x_1, x_2, \ldots, x_n\}$ and we want to associate each criterion x_i with a weight w_i based on $n \times n$ comparisons gathered in a comparison matrix A. The principal eigenvector w is acquired by solving the system of equations:

$$(A - \lambda_{\max} I)w = 0 \tag{1}$$

where I is the unit matrix; $\lambda_{\max}$ the largest or principal eigenvalue of A; and w the principal eigenvector (vector of priority factors). For more details, see Saaty (1994, 2003), Winston (1994) or Handfield et al. (2002).

The comparison of criteria was conducted through an interdisciplinary cooperation of 52 experts from universities, the Ministry of Environment, institutions for ecological research and other organisations for studying and protection of the environment. The criteria estimations were assessed according to all categories of environmental burden in which the estimated parameter appears. The accepted estimations thus addressed this problem in its widest possible extent. The gathering of expert estimations was carried out with the Delphi method (Pečjak 2001; Ronde 2003; Khorramshahgol 1999). The method anticipates gathering data in several rounds, which are described next.

2.3.1 Questionnaire for pairwise comparisons of criteria

The first round was aimed at obtaining pairwise comparisons of all criteria in the model. Given the structure of the model, we prepared a questionnaire that asked the 52 experts to compare pairs of criteria appearing at individual levels of the model. Figure 1 shows a part of the questionnaire addressing the level of the emissions (considering solid wastes, waste air, emissions to waters and energy emissions). The instructions for completing the questionnaire were as follows: “It is well known that in manufacturing of wood products there occur impacts on the environment. Please make a pair-wise comparison of different criteria. Please indicate which of the enumerated criteria presents a greater impact on the environment and what is the difference in the intensity of the impact of that criterion in comparison with the other one, measured on a scale from 1 to 9.”

In presenting the pairwise comparison estimations, three possible groups of answers are possible:

(a) The two criteria have the same impact on the environment. This means that there is no difference between the intensity of the environment impact, meaning the ratio between the two criteria is 1:1 or the estimation is 1, situated in the middle of the assessment scale shown in Fig. 1.

(b) The criterion on the left-hand side of the assessment scale has a greater impact on the environment than the criterion on the right-hand side. This means that the ratio of impact intensity of the left criterion against the right criterion is from 2:1 to 9:1 or the estimation is from 2 to 9 on the left side of the scale shown in Fig. 1.

(c) The criterion on the right-hand side has a greater impact than the one on the left-hand side. The ratios are reciprocal to the ratios in case (b).

The results of this round were pairwise comparison estimations of the criteria.

2.3.2 Gathering of expert estimations and the results of pairwise comparisons

The aims of the second round were to determine the weights of criteria whose estimations were gathered in the previous round and to confront opinions of the cooperating experts. First, we verified the consistency (Saaty 1994) of each expert's estimation separately. We processed individual pairwise comparisons statistically and calculated the average value, median, interquartile range, minimal and maximum assessment. We presented these quantities graphically in the questionnaire: We added a box-and-whisker plot for each question (see an example in Fig. 2). These marks provide additional information for the expert who makes the assessment. The cross in the box represents the average value, the edges of the box indicate the 25th and 75th percentiles (first and third quartiles), and the whiskers represent the 5th and 95th percentiles of the distributions. The squares represent outliers.

The extended questionnaire was then passed to experts for reconsideration. We obtained a new set of pairwise comparisons and processed them in the same way as before. If the provided estimations of an expert were inconsistent or deviated strongly from the average estimation, we met with the expert again in the third round. We presented them other experts' estimations and statistical values and gave them a chance/the possibility to modify their estimation. We repeated this process until the estimations were satisfactory and consistent. In order to reduce individual estimation

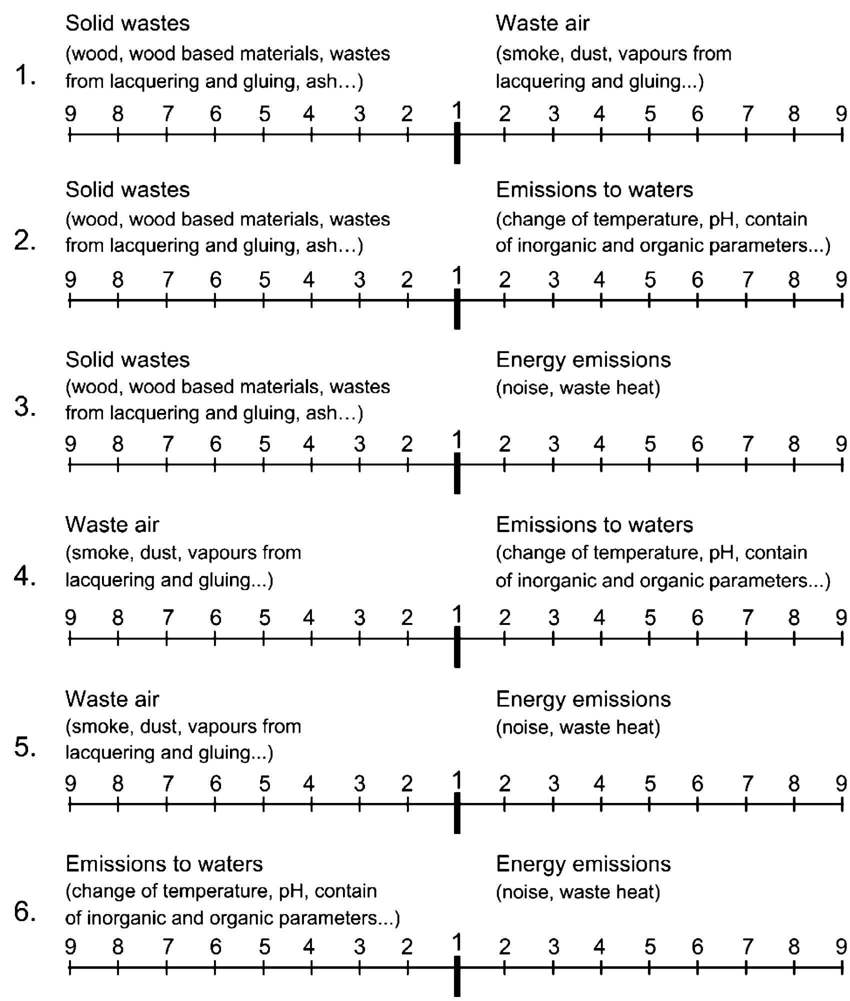
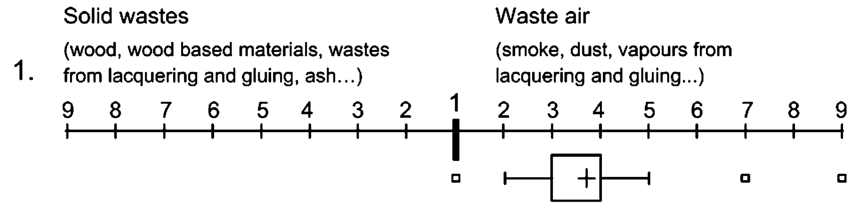


Fig. 1 Part of the questionnaire for experts: first round of pairwise comparisons

Fig. 2 An example of question for the second round of pairwise comparisons



subjectivity, we used mean estimation values of the impact intensity ratio. For the measure of the variable mean, we used the median which is the most representative mean measure for data measured with an ordinal unit scale (Košmelj 2001). The consistency for the calculated mean values was verified again.

2.3.3 Pairwise comparisons and priority factors

From the mean values of the impact intensity ratio, we constructed overall pairwise comparison matrices. For example, the pairwise comparison matrix for the emissions level was as follows:

$$A = \left[\begin{array}{ccccc} & \textit{Solid wastes} & \textit{Emissions to waters} & \textit{Waste air} & \textit{Energy emissions} \\ \textit{Solid wastes} & 1 & 1/4 & 1/3 & 3/1 \\ \textit{Emissions to waters} & 4/1 & 1 & 2/1 & 5/1 \\ \textit{Waste air} & 3/1 & 2/1 & 1 & 5/1 \\ \textit{Energy emissions} & 1/3 & 1/5 & 1/5 & 1 \end{array}\right].$$

After solving the system of Eq. 1—calculation with ExpertChoice software—we get the vector of priority factors w:

$$w = \left[\begin{array}{cc} \textit{Solid wastes} & 0.1361 \\ \textit{Emissions to waters} & 0.4832 \\ \textit{Waste air} & 0.3148 \\ \textit{Energy emissions} & 0.0659 \end{array}\right].$$

These priority factors are entered as local priority factors into the corresponding parts of the model presented in Fig. 3.

2.4 Generation of entry functions

The criteria found at the lowest levels of the model are the entry criteria. For these, the real values u_{ik} entering the model need to be collected for each wooden product k and each entry criterion x_i. They usually differ in quantity and have different units of measure. For this reason, additional functions need to be introduced for these criteria converting the values u_{ik} into the preference values P_{ik}. The preference value P_{ik} is a non-dimensional value expressing the desirability within the framework of our decision. In our model, we used adjusted linear functions:

$$P_{ik} = \frac{d_i \times u_{ik}}{pv_i \times 10,000} \qquad (2)$$

where P_{ik} is the preference value of the criterion x_i for the alternative k; u_{ik} is the real value of the criterion x_i for k; and pv_i is a unit of measurement for x_i (needed to cancel the unit of u_{ik}). The coefficient d_i is obtained with the equation:

$$d_i = pn_1 x pn_2 x pn_3 x \ldots x pn_m \qquad (3)$$

where pn_i is the number of sub-criteria on the i-th level of the model. Entry functions are denoted ‘P’ in Fig. 3.

2.5 Calculation of the final estimate

Once the data for all entry criteria have been collected, we first render these real criteria values into preference values P_{ik} (Eq. 2) and then with the help of weight factors w_i gradually aggregate them to higher and higher levels of the model. The estimation of environmental burden W_h for a criterion occurring at a higher level of the model is calculated as:

$$W_\mathrm{h} = \sum_{i=1}^{n} w_i \times P_{ik} \qquad (4)$$

where w_i and P_{ik} are weight factors and preference values of subordinate criteria, respectively. The final estimate of a wooden product is then represented by the preference value of the root criterion. The lower the estimate, the least impact on the environment and, consequently, the more desirable the alternative.

3 Results

The final model is shown in Fig. 3. In addition to the names and structure of criteria, which follow the decomposition

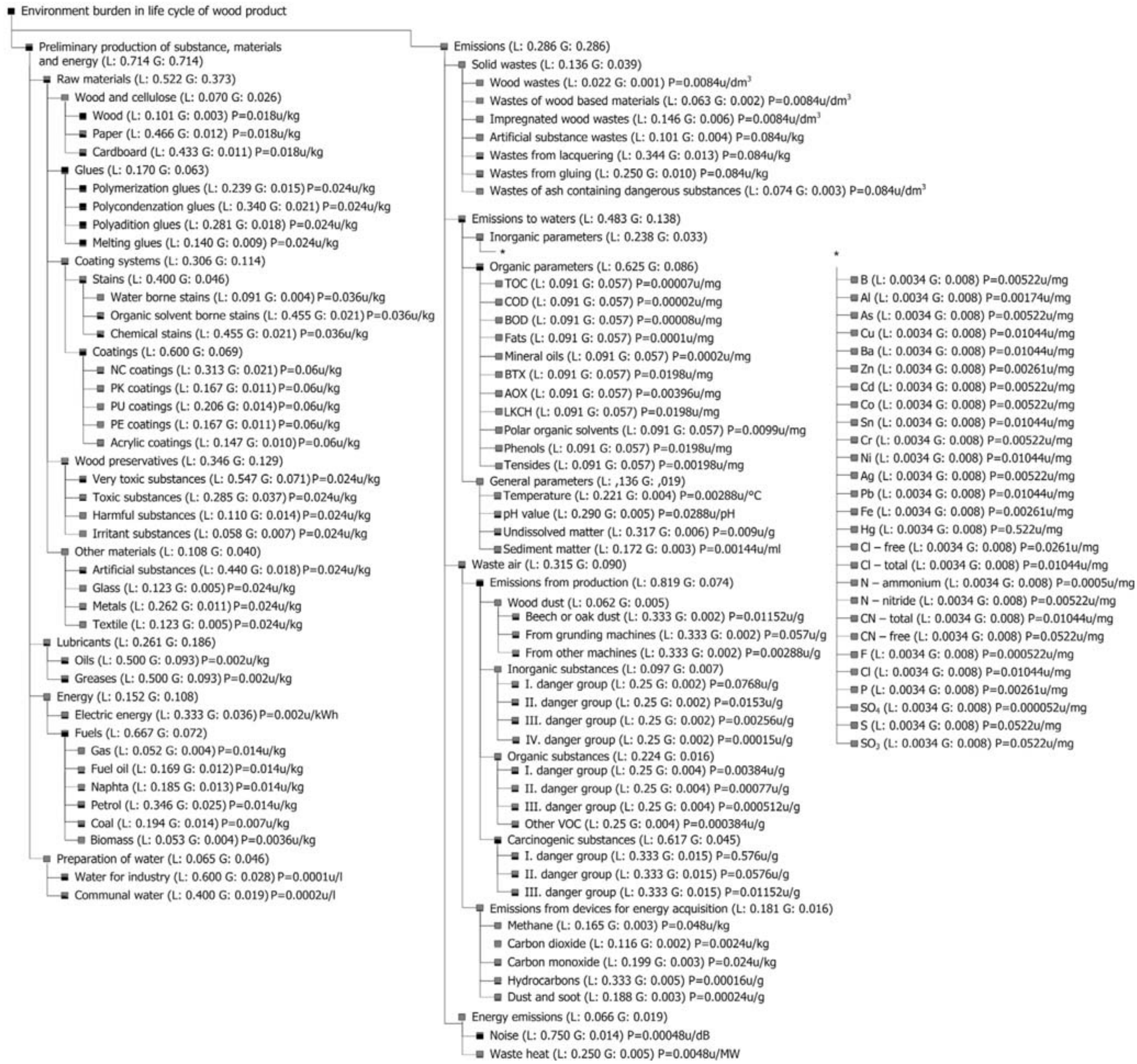


Fig. 3 Multi-criteria decision-making model for classifying wood products according to their influences on the environment

outlined in Section 2.2, Fig. 3 displays priority factors in the form of local (L) (calculated as described in Section 2.3.3) and global weights (G; local weights multiplied with upper levels weights according to the AHP methodology). For entry criteria, entry functions P (Eq. 2) are presented too.

The model has been applied and evaluated in three types of applications. The first type involved the already published cases from literature and was conducted mainly to verify the model and explore its potential (Lipušček 2005). The remaining two types addressed real cases from Slovene wood manufacturing companies. With one type, we analysed different product concepts in three companies with the purpose of providing support in decision making for the environmentally most suitable product concept. With the other type, we studied products which serve the same function but are produced by different companies, with the purpose of finding out which company produces more environmentally friendly products.

4 Discussion

A comparison of weights in the model reveals that according to experts' opinion, a preliminary production of auxiliary materials and energy consumption represents the

biggest impact of wooden products on the environment. By studying the former criterion into more detail, we can determine that the most problematic are preservatives, coating systems and glues. With respect to the production of energy, the most problematic are the use of gasoline and petroleum. In the case of emissions, the experts believe that in Slovenia, the biggest impact on the environment represents the impact on water and air, whereas solid wastes and energy emissions are of a lesser importance. With wastewaters, the biggest impact on the environment is represented by the presence of organic criteria. With waste air, more attention is given to waste air appearing directly in the production and less to smoke gases resulting from devices for acquiring heat and electrical energy. In environmental burden with waste air from production, the environment is impacted the most in so far carcinogenic substances appear. A lesser impact is represented by organic substances and even a lesser one by inorganic substances and dust. With smoke gases, the most questionable are sulphur dioxide and nitrogen oxides, followed by carbon oxide, dust and soot. With solid wastes, the biggest impact on the environment is represented by waste from lacquering, followed by waste from gluing and impregnated wood waste. With energy emissions, noise represents a much bigger impact on the environment than emissions of waste heat.

The presented model includes the criteria that we and the contributing experts considered the most important for the assessment of environmental burden appearing in wood industry. However, there might be a need for including additional criteria, in particular if the model has to be adapted to environments other than Slovenia or to address other than wooden products. The MCDM approach enables a relatively easy way to add new criteria. In such a case, the additional criterion is placed at some level of the model and only the additional criterion must be compared in a pairwise way with the existing criteria at that level. This is followed by a recalculation of priority factors that are utility functions for that changed part of the model. There is no need to change utility functions at other parts of the model.

The model is developed for entering numerical data measured for the compared alternatives (wood products). If exact numerical values (parameters) for a criterion are impossible to obtain, then pairwise comparisons can be carried out for this criterion between the alternatives in the same way as in Section 2.3, except that we compare alternatives instead of criteria. In this way, we can ensure entry data for immeasurable criteria as well. However, the results in this case are only comparable between the alternatives included in the calculations, whilst the results of parallel calculations are not comparable.

5 Conclusions

The represented multi-attribute model is aimed at classifying products according to their environmental burden in the entire wood product life cycle. The model contains all the most important criteria of environmental burden present in the wood industry. The model facilitates a critical comparison of products from the point of view of environmental burden. For each wooden product, we obtain a relative assessment of its environmental burden that enables a comparison of a set of considered wooden products. The comparison can be carried out not only at the level of entire products but is also decomposed into a number of hierarchically structured criteria, such as environmental impact during preliminary production, materials and energy used, emissions, etc. Such comparison reveals distinctive advantages and disadvantages of a product compared to others.

The model was developed according to the principles of MCDM which enables easy deduction and addition of new criteria into the model if the model turns out to be set too widely or too narrowly. In the case of adding new criteria, these are set at the terminal level of the hierarchy. In other words, the changes affect the model only locally.

The model is designed for the entry of numerical data which are measured for all the compared products. However, if these values cannot be measured directly for some criteria, the AHP method enables the acquisition of criteria weights indirectly, i.e. by pairwise comparisons of products for those criteria. In this way, the model can operate with non-numerical (descriptive or estimated) values too.

The MCDM methodology also enables the sensitivity analysis of the final estimations to the changes of priority factors at any level of decision making. The presented model thus enables a critical judgement of products inside an organisation, ranking of product concepts and a comparison of wood products with substitute products. The model of classifying products according to their environmental burden can serve as support in choosing among the alternatives and deciding on a product, which in its entire life cycle, not only in an individual stage, represents the least impact on the environment. The model can also be used as help in judging the ecological quality of products.

The model has been developed by Slovenian experts and specifically addresses local conditions and legislation of the Republic of Slovenia. This is clearly a limitation of the model, and an adaptation of the model would be needed to address other environments, countries or product types.

6 Recommendations and perspectives

We believe that parts of the model that address preliminary production of substances, materials and energy (approximately the first column in Fig. 3) are fairly common and can be relatively easily adapted to other countries or immediately used for some preliminary assessments at least. However, the other part (emissions) highly depends on Slovenian legislation and would therefore need a more elaborated reconstruction for other countries.

In order to compare wood products with other alternative or substitutive products, the list of criteria had to be expanded to the levels of other materials and to the field of disposal of waste materials in solid state.

In further work, it would be reasonable to engage an additional criterion of working condition at the production of materials. The working conditions could contribute to the evaluation of environmental suitability and may address the following aspects: production of materials, semi-finished goods and products, users of products and workers who remove or destroy disposed products.

Finally, the presented model does not address socioeconomic consequences of production which could also be included as a new model component.

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